EXHIBIT C

An aluminium nitride light-emitting diode with a wavelength of 210 nanometres

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Compact high-efficiency ultraviolet solid-state light sources[1]—such as light-emitting diodes (LEDs) and laser diodes—are of considerable technological interest as alternatives to large, toxic, low-efficiency gas lasers and mercury lamps. Microelectronic fabrication technologies and the environmental sciences both require light sources with shorter emission wavelengths: the former for improved resolution in photolithography and the latter for sensors that can detect minute hazardous particles. In addition, ultraviolet solid-state light sources are also attracting attention for potential applications in high-density optical data storage, biomedical research, water and air purification, and sterilization. Wide-bandgap materials, such as diamond[2] and III–V nitride semiconductors (GaN, AlGaN and AlN; refs 3–10), are potential materials for ultraviolet LEDs and laser diodes, but suffer from difficulties in controlling electrical conduction. Here we report the successful control of both n-type and p-type doping in aluminium nitride (AlN), which has a very wide direct bandgap[11] of 6 eV. This doping strategy allows us to develop an AlN PIN (p-type/intrinsic/n-type) homojunction LED with an emission wavelength of 210 nm, which is the shortest reported to date for any kind of LED. The emission is attributed to an exciton transition, and represents an important step towards achieving exciton-related light-emitting devices as well as replacing gas light sources with solid-state light sources.

Recently, we have achieved n-type conduction in Si-doped AlN (refs 12, 13). In the present work, by reducing the dislocation density and finely controlling the Si doping level, we were able to boost the room-temperature electron mobility. We examined (by Hall-effect measurement) the temperature dependence of the electron concentration (n) and electron mobility (μ_n) for n-type Si-doped AlN with a Si doping concentration of 3.5×10^{17} cm^{-3}. At 300 K, the electron concentration was 7.3×10^{14} cm^{-3}. The electron mobility was 426 cm^2 V^{-1} s^{-1}, which is the highest reported to date in n-type AlN and attests to the high quality of the AlN. As the temperature increased, the electron concentration increased exponentially and saturated at higher temperatures (Fig. 1a). The temperature dependence of electron concentration was fitted by the least-squares method, assuming the charge neutrality equation for n-type semiconductor with a shallow donor and a deep compensating acceptor[12]. The best-fit values are donor concentration $N_D = 3.0 \times 10^{17}$ cm^{-3}, acceptor concentration $N_A = 2.6 \times 10^{16}$ cm^{-3} and donor ionization energy $E_D = 282$ meV. The donor concentration agreed well with the Si doping concentration, indicating that almost all Si atoms act as donors in AlN. The compensation ratio N_A/N_D was about 0.1. On the other hand, the electron mobility increased monotonically as temperature decreased (Fig. 1b). At 220 K, the electron mobility reached 730 cm^2 V^{-1} s^{-1}. In calculating mobility, we took into account scattering by neutral impurities, ionized impurities, polar optical phonons, acoustic deformation potential, and piezoelectric potential[13]. We assumed Matthiesen's rule, and used the best-fit values of N_D, N_A and E_D, and the material parameters in ref. 13. The calculated electron mobility (solid line) agreed very well with the measured one. For n-type AlN with a higher dislocation density, the measured electron mobility was much smaller than the calculated one owing to the influence of scattering caused by charged dislocations[14] or unidentified dislocation-related defects. Thus, the agreement indicates that the quality of the n-type AlN layer is high.

With this success in achieving n-type conduction, we turned our attention to p-type conduction and found that Mg doping produced p-type AlN. The p-type conduction in Mg-doped AlN was observed at Mg doping concentrations below 2×10^{20} cm^{-3}. When the Mg doping concentration exceeded an upper limit of 2×10^{20} cm^{-3}, the Mg-doped AlN became highly resistive. This is similar to the tendency observed in n-type Si-doped AlN (ref. 12), and probably results from a self-compensation effect of Mg in p-type AlN. This indicates that control of the Mg doping concentration is important for obtaining p-type conduction. In addition, the as-grown Mg-doped AlN was highly resistive, and became p-type conductive after thermal annealing in N_2 at 800 °C for 10 min. For the highly resistive as-grown Mg-doped AlN, the H concentration was in the same range as the Mg concentration, and after annealing the H concentration decreased. This means that, in the as-grown AlN, H passivated Mg dopant, but after annealing H was desorbed and Mg was activated, as in GaN (ref. 15).

We measured the temperature dependence of hole concentration (p) and hole mobility (μ_p) for Mg-doped AlN with a Mg doping concentration of 2×10^{19} cm^{-3}. We clearly confirmed p-type conduction from the polarity of the Hall voltage, although there is some scattering of measured values because of the high resistivity (low

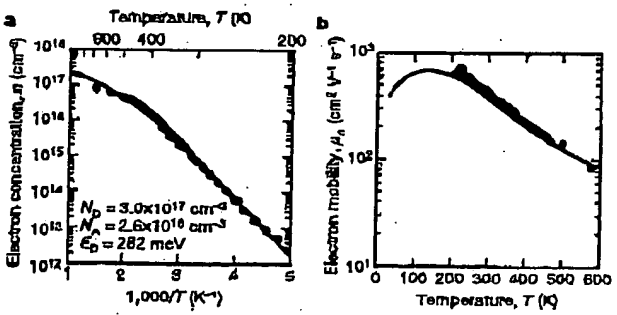

Figure 1 | Electrical characteristics of n-type Si-doped AlN. a, The temperature dependence of electron concentration. The solid line shows the least-squares fit, assuming the charge neutrality equation with a shallow donor and a deep compensating acceptor. The best-fit parameters are shown. b, The temperature dependence of electron mobility. The solid line shows the calculated mobility, considering specific scattering mechanisms (see text).

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